<Transmission electron micrograph of the yttrium-iridium system at the composition $Y_{.05}$ $Ir_{.95}$(24 000X). TEM by Dorothy S. Garinger.

High-Temperature Superconductivity:
A Metallurgical Approach

by Angelo L. Giorgi, Gregory R. Stewart, James L. Smith, and Bernd T. Matthias

A mysterious 30-fold enhancement of the critical temperature in the yttrium-iridium system has been traced to the formation of a eutectic structure and to a dramatic decrease in the stiffness of the crystal lattice.

Superconductivity is the sudden complete disappearance of electrical resistance in some materials when they are cooled below a critical temperature. This phenomenon (Fig. 1) has intrigued solid-state scientists, metallurgists, and engineers ever since its discovery by Kammerlingh Onnes in 1911. Visions of many possible applications of superconductivity to electrical power generation and distribution, fusion reactors, high-energy particle accelerators, and propulsion systems, and of the many new superconducting devices have provided a powerful stimulus to the search for superconducting materials with high superconducting critical temperature (T_c). Development of a microscopic theory on superconductivity (the BCS theory) in 1957 brought hope that the theory would prove useful in predicting new high T_c materials. Unfortunately, none of the predictions have been successful. Many of the new high T_c superconductors shown in Table I, which form the basis for the present superconducting

technology, were discovered by application of Matthias' Rule, an empirical rule developed in the 1950s. This rule relates the T_c of elements, alloys, and compounds to their average number of valence electrons per atom (e/a) as shown in Fig. 2.

In 1964, when workers at the Bell Laboratories were examining mixtures of the two metals yttrium and iridium as part of a study of the relationship between the T_c and the e/a ratio, they made a puzzling observation. When they added as little as 1 atomic per cent yttrium to iridium, the temperature at which the material became a superconductor quickly increased from 0.1 K to above 3 K. When they increased the amount of yttrium to 33 atomic per cent, the T_c remained at 3 K. What was causing this 30-fold increase in the superconducting critical temperature? The enhanced superconductivity was certainly not due to the small change in the e/a ratio produced by the addition of yttrium, nor could it be explained from the known materials in the system. The iridium T_c is
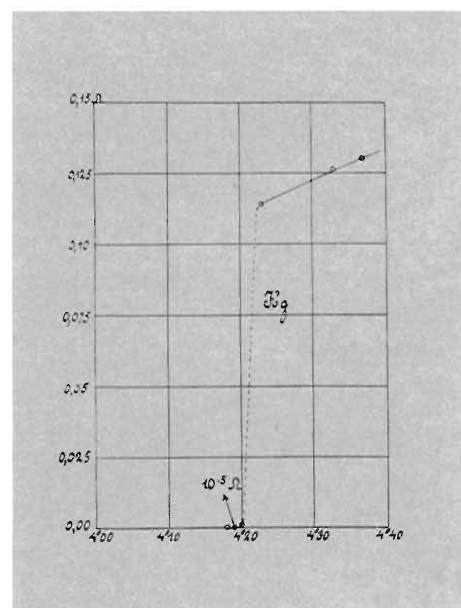

Fig. 1. A reproduction of Onnes' original data, which marked the discovery of superconductivity in 1911. The plot of resistance in ohms vs absolute temperature shows the complete disappearance of electrical resistance in mercury at 4.2 K.

only 0.1 K, and neither yttrium nor YIr_2 (the only known compound in the system) become superconductors even when they are cooled to 0.3 K. The immediate conclusion was that another compound, probably with a composition close to YIr_4, must exist and that this hypothetical phase was the source of the superconductivity. Many samples, prepared with compositions varying between iridium and YIr_2, were heat treated and examined by x-ray diffraction. All attempts to discover a new phase were unsuccessful. The source of the enhanced superconductivity

HIGH T_c SUPERCONDUCTORS

Compound	T_c (K)	Compound	T_c (K)
Nb_3Ge	23.2	$NbC_{.25}N_{.75}$	17.8
Nb_3Ga	20.3	Nb_3Al	18.8
$Nb_3Al_{.8}Ge_{.2}$	20.1	V_3Ga	16.5
Nb_3Sn	18.1	V_3Si	17.1

Fig. 2. Empirical behavior of T_c as a function of the average number of valence electrons per atom (e/a) for pure elements and alloys. This empirical relationship was discovered by B. T. Matthias in 1957.
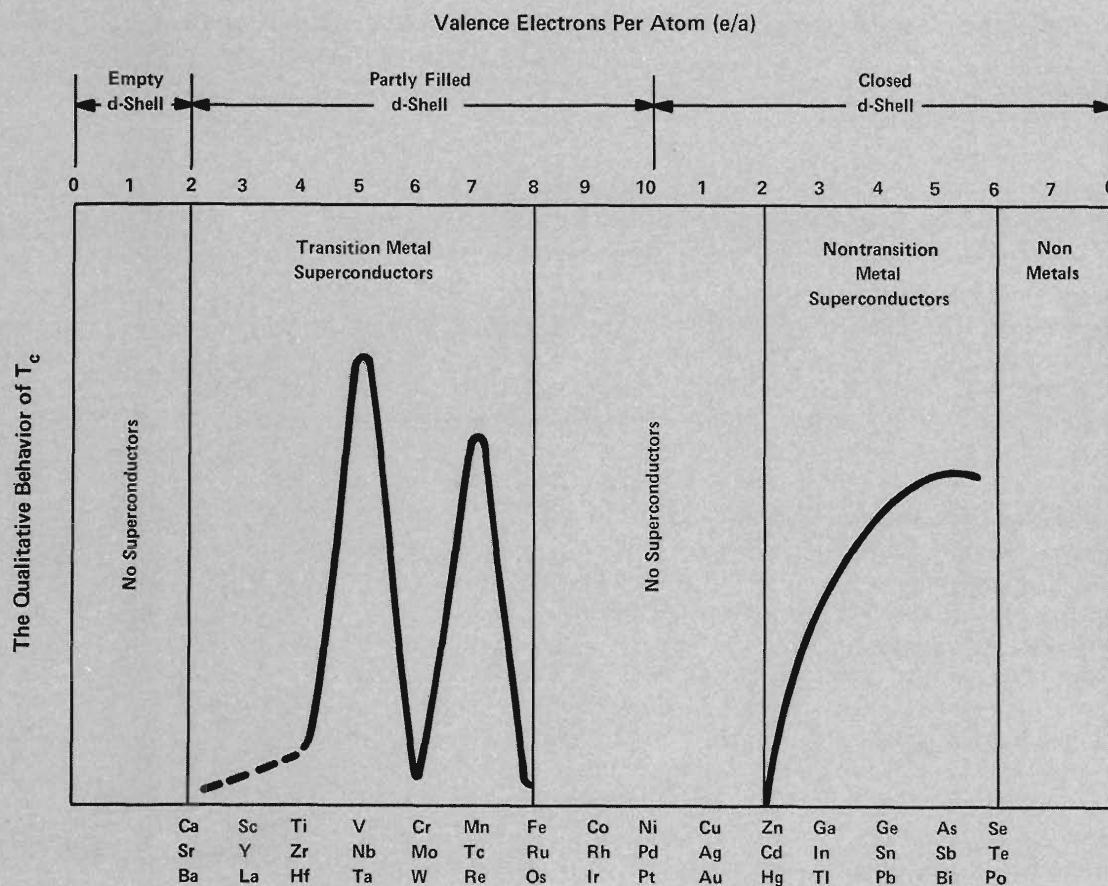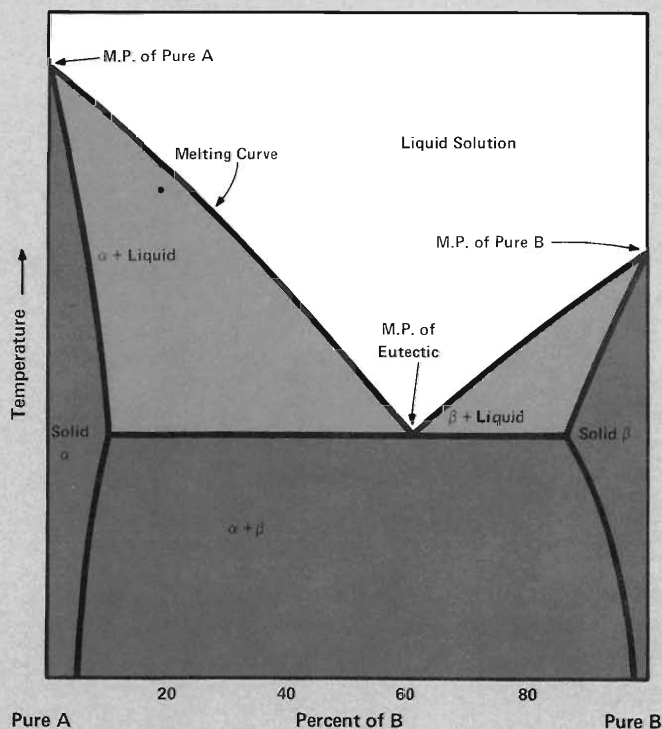
*Fig. 3. A typical phase diagram for a mixture of metals showing melting point (M.P.)
minimum at the eutectic composition. Solution of B into A lowers the M.P. of A;
similarly, solution of A into B lowers the M.P. of B. Solid α is a solid solution of B
atoms dissolved in the crystal lattice of A. Solid β is a solid solution of A atoms in the
crystal lattice of B.*

Measurement Techniques

Reviewing some of the techniques used to measure the superconducting critical temperature will help explain the problems associated with a study of this type. At present there are over a thousand known superconducting materials. Their critical temperatures range from minimum values of a few millidegrees above absolute zero to the present maximum value of 23.2 K. Most of these materials are intermetallic alloys; that is, they are mixtures, compounds, or solid solutions of two or more metals.

The three methods used most commonly to determine superconductivity in such materials are based on three distinctive thermal and electromagnetic properties of the superconducting state:

1. The complete disappearance of electrical resistance.
2. The complete exclusion of magnetic fields, up to some critical value H_c, from the body of the superconductor.
3. A sharp increase in the electronic specific heat of the superconductor at T_c owing to the marked decrease in the entropy.

In the method based on resistance, the sample is fashioned into a rod or wire and a fixed current is passed through it. As the temperature is lowered, the voltage across the sample is monitored by the four-probe technique illustrated in Fig. 4. When the material becomes
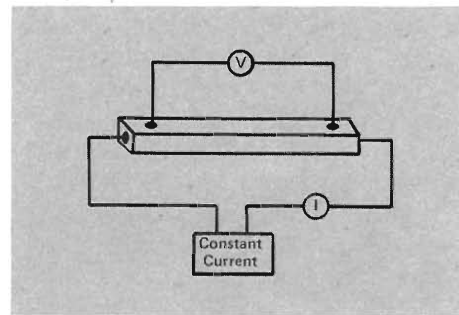
remained a mystery. The investigation was finally abandoned and all but forgotten.

This year, when interest in the Y-Ir system was revived, a much more thorough study was conducted at the Los Alamos Scientific Laboratory (LASL) in collaboration with the University of California (UC) at La Jolla, California. The careful characterization of the various compositions was extended to include low-temperature specific heat measurements, metallographic examination, and transmission electron microscopy as well as the usual x-ray diffraction and magnetic susceptibility measurements. From this study, we have learned that the source of the enhanced superconductivity in the Y-Ir system is a eutectic structure consisting of a mixture of iridium and the neighboring phase, YIr_2.

A eutectic is the unique mixture of two constituents, usually metals, that has the lowest melting point. Eutectics have been known since the days of the Roman Empire and have been in continued use since then. Bronze and solder are common examples. A typical phase diagram for a eutectic mixture is shown in Fig. 3. The melting point for the eutectic composition is considerably lower than for either constituent.

The low-temperature specific heat measurements on the Y-Ir samples disclosed that, with the formation of the eutectic structure, the stiffness of the lattice decreases dramatically. The enhanced superconductivity probably is a result of the lattice softening. This intriguing solution to the mystery promises a new investigative approach to high-temperature superconductivity.

Fig. 4. Four-probe technique for measuring the change in electrical resistance as a sample becomes superconducting.

superconducting, the resistance and, therefore, the voltage suddenly drops to zero. The temperature at which the drop occurs is the T_c of the material. This method suffers from a demonstrated weakness. It requires a continuous superconducting path across the material, and it gives no indication of how much of the material is superconducting. Quite often the bulk of a material is not superconducting but instead contains microscopic filaments in a superconducting phase. A resistive measurement on such a sample gives results similar to those for a true bulk superconductor because the filaments, having zero resistance, short-circuit the sample and cause the voltage to drop to zero. Using x-ray diffraction to determine the phases present in a sample also can be misleading. If, as is often the case, the filaments in the superconducting phase represent only a small fraction of the total sample, their concentration may lie below the detection limit, and the x-ray diffraction pattern will indicate that the nonsuperconducting bulk material is the only phase present. An investigation limited to these techniques can lead to the erroneous conclusion that the phase representing the bulk material is the superconductor.

A much more widely used technique is the ac susceptibility method, based on the exclusion of magnetic fields (Fig. 5). A stable alternating current of less than 60 hertz is applied to the primary of a sensing coil. The output from two matched secondary coils, connected in opposition, is fed to the input of a frequency-locked amplifier. A small variable mutual inductance is connected between the primary and secondary circuits and adjusted to cancel out any residual imbalance in the secondary circuit. The sample, which can be a powder or solid, is placed in one of the secondary coils and cooled slowly. A sharp change in the sample's magnetic permeability at T_c causes an imbalance in
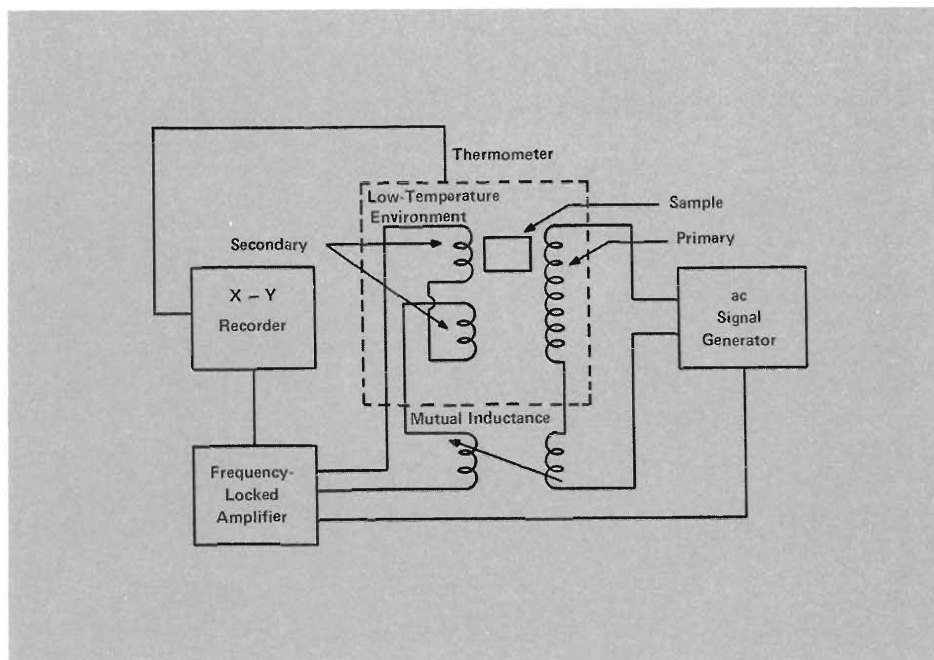

Fig. 5. Technique for measuring the change in magnetic permeability of a sample when it becomes superconducting. A rapid change in the electrical signal from the secondary coils caused by expulsion of the magnetic field from the sample indicates the onset of superconductivity.

the secondary circuit, which results in a signal at the output of the amplifier. Because the signal is proportional to the change in magnetic permeability, it gives a semiquantitative value of the amount of superconductor in the sample.

The ac susceptibility method is preferred over the resistive method because it detects superconductivity in the individual particles and does not depend on a continuous superconducting path. However, even this method can give misleading results. Occasionally, a superconducting phase is deposited as a thin film at the grain boundaries of a bulk material. When the film completely encloses the grains, it acts as a superconducting *can*; that is, it prevents any magnetic flux from penetrating into the *canned* bulk material. Under these conditions, the signal strength from the amplifier suggests that all the material is superconducting.

The method generally accepted as giving a true indication of both the presence and amount of superconducting material is measurement of the variation of the low-temperature specific heat with temperature (Fig. 6). The specific heat (C) is the amount of energy (dQ) required to raise the temperature of a unit mass (usually a mole) of material by a small increment (dT).

$$C = dQ/dT . \qquad (1)$$

The specific heat of a metal has two contributions, one from the thermal motion of the electrons surrounding the lattice and one from the lattice vibrations. For a normal metal, the two contributions to the specific heat C_n have a well-known temperature dependence.

$$C_n = \gamma T + \beta T^3 , \qquad (2)$$

where γ depends on the properties of the electrons and β depends on the crystal lattice. As shown in Fig. 7, these parameters are determined by plotting C_n/T vs T^2. The slope of the resulting straight-line-curve is equal to β and the intercept is γ. The information about the normal-state properties contained in these two parameters is discussed later.

When the metal becomes superconducting, the lattice contributions to the specific heat (βT^3) remain the same, but the electronic contributions (γT) change dramatically. The specific heat (C_s) for the superconducting phase is given by

$$C_s = ae^{-\Delta/kT} + \beta T^3 . \qquad (3)$$

The electronic term for a superconductor is clearly different in temperature dependence. The difference is due to the for-

mation, at T_c, of an energy gap (Δ) in the allowable energy levels that the electrons can occupy in the material. Bound electron pairs of opposite spin and momentum (Cooper pairs) form at T_c and occupy energy levels below the energy gap. Energy is needed to break up the pairs and raise them to energy levels above the energy gap. Since $ae^{-\Delta/kT}$ is usually more than twice as large as γT, the change in the electronic contributions at T_c causes a marked discontinuity in the specific heat curve (Fig. 7). The discontinuity is the best indication of the presence of a superconducting state.

A generally accepted result of the BCS theory is that, for 100% bulk superconductivity,

$$ae^{-\Delta/kT_c}/\gamma T_c = 2.43 . \tag{4}$$

Thus the ratio of the electronic specific heats at T_c can be used to estimate the amount of the sample that has become superconducting and to rule out ambiguities caused by either microscopic amounts of one-dimensional paths in the resistive method or two-dimensional grain boundary cans in the ac susceptibility method. Further, if x-ray diffraction indicates the presence of a second phase, the amount of second phase estimated from a comparison of the relative intensities of the diffraction patterns can also be compared to the ratio of the electronic contributions to the specific heat.

A much more accurate estimate of the amount of superconducting material is possible for materials with T_c values at least four times greater than the lowest temperature to which the specific heat can be measured (for example, a $T_c \geq$ 4.8 K and a lowest temperature of 1.2 K). The superconducting phase contributes significantly to the specific heat at T_c, but its contribution dies away exponentially as the temperature drops below T_c, when the only terms left in the specific heat behavior vs temperature expression are βT^3 and any γT contribution from nonsuperconducting material. The ratio of this remnant γT to the value of γT above T_c, where the sample is 100% nonsuperconducting, is the exact fraction of the material that is nonsuperconducting.
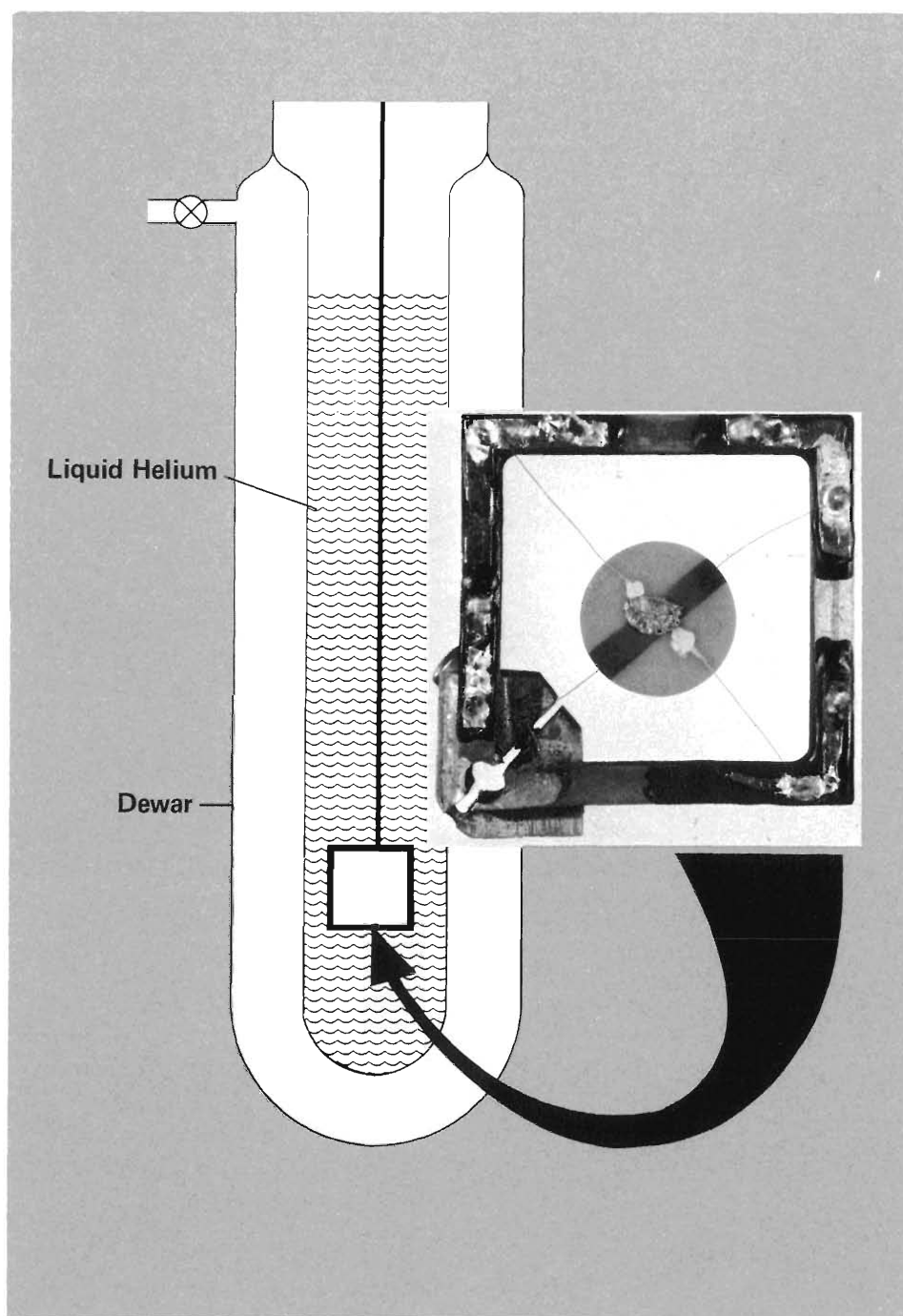

Fig. 6. *Technique for measuring low-temperature specific heat. The sample, mounted on a sapphire disc 25 μm thick, is suspended in the center of a metal frame by 75-μm-diameter gold wires. The gold wires isolate the sample and platform thermally while providing two separate electrical connections to the metal frame. One connection supplies heat to the sample and platform through a film heater (the dark strip across the platform). The other connection measures the change in temperature by monitoring the change in resistivity of a germanium thermometer. The heat is supplied to the sample and platform in fixed increments by pulses of electrical energy to the film heater. Since sapphire is an excellent thermal conductor, sample and platform equilibrate rapidly after each pulse. By measuring the changes in temperatures for fixed increments in energy, the specific heat for the platform and sample is measured as a function of temperature. The total specific heat minus the known specific heat of the sapphire platform is the specific heat of the sample.*
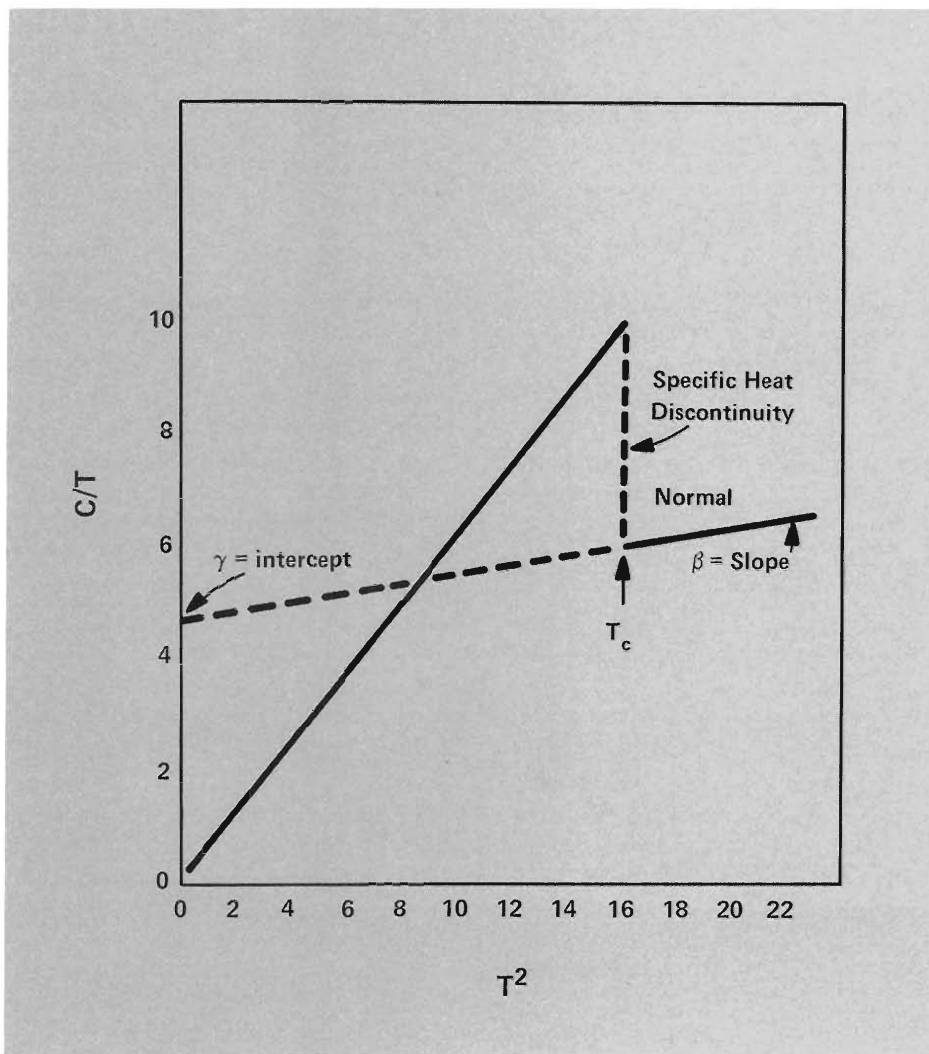
Fig. 7. Idealized specific heat curve for a superconductor with $T_c \approx 4.0$ K. A significant jump occurs at T_c. In the absence of a superconducting transition, the specific heat curve follows the dashed line and intercepts the ordinate at γ Near absolute zero, the lattice contributions go to zero rapidly, and the specific heat is due almost entirely to the electrons.

Fig. 8. Measured values of the specific heat for the $Y_{.10}Ir_{.90}$ system. Compare these measurements with the idealized curve in Fig. 7.

Importance of γ and β

Obviously, certain properties of materials in their normal state must lead to the electrons' overcoming their repulsive Coulomb interaction to form Cooper pairs and create the energy gap Δ at the superconducting transition. The purely theoretical considerations have been studied extensively and all known normal-state properties of various superconductors have been compared systematically. As a result, workers in the field are beginning to understand which properties are important for the superconducting state. The parameters γ and β determined by low-temperature specific heat measurement are found to be very important.

The parameter γ is proportional to N(0), the number of electrons at the most highly populated energy level (the Fermi level) in the normal-state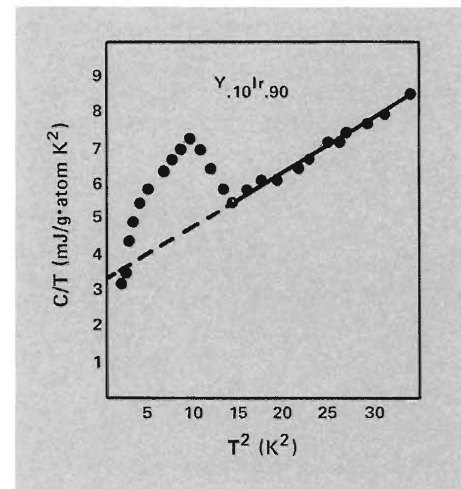 material, and to $(1 + \lambda)$, which depends on how strongly the material's electrons are tied to its lattice; it is given by

$$\gamma = \text{const.} \times N(0) \times (1 + \lambda). \qquad (5)$$

The parameter β is a measure of how stiffly the ions are held in place in the lattice by the material's electronic forces; it is given by

$$\beta = \text{const.}/\theta_D^3, \qquad (6)$$

where θ_D is the characteristic Debye temperature. The term θ_D was first introduced in a model of lattice vibrations proposed by Debye in 1912. The model describes the motion of the lattice ions by a superposition of quantized elastic waves propagating through the lattice. The quanta of elastic waves are called *phonons*. The Debye temperature, which is related to the cut-off frequency, can be thought of as the temperature at which the lattice forces responsible for the lattice stiffness are too weak to hold the ions in their places. Thus lead, a soft material, has a low θ_D (108 K), whereas iron, a hard material, has a high θ_D (464 K).

In 1957 Bardeen, Cooper, and Schrieffer developed the BCS microscopic theory of superconductivity and succeeded in relating T_c to γ and β.

$$kT_c = 1.14\, \hbar <\omega> \exp\left[-1/N(0)V\right], \quad (7)$$

where $\hbar$ is Planck's constant, $<\omega>$ is some average of the lattice phonon frequency related to θ_D, $N(0)$ is the electronic density of states at the Fermi surface, and V is the electron phonon interaction parameter. On this basis it was assumed that materials with high $N(0)$ (high γ) and high θ_D (high β) would be high T_c materials.

Solution of the Y-Ir Mystery

Events leading to discovery of the source of the enhanced superconductivity in the Y-Ir system produced a number of false leads. They demonstrate why low-temperature specific heat and metallographic examinations are vital to any critical study of superconducting materials. We had long known that the addition of as little as 1 atomic per cent yttrium to iridium metal raises the inductive and resistive T_c from 0.1 K to over 3 K. More recent LASL-UC, La Jolla, studies showed that the behavior is similar when europium is substituted for the yttrium; that is, the addition of a very small amount of europium to iridium causes a dramatic increase in the T_c. This new result rekindled interest in both the Eu-Ir and Y-Ir systems. We chose the Y-Ir system for a complete study of this novel effect because of the apparent absence of significant second phase for compositions as rich in yttrium as 10 atomic per cent and the absence of superconductivity in YIr_2, above 0.3 K.

We remeasured Y-Ir compositions from $Y_{.01}Ir_{.99}$ to YIr_2 using the ac susceptibility method. The signal magnitude in these measurements first increased with increasing yttrium concentration, reaching a maximum value near the $Y_{.20}Ir_{.80}$ composition and then decreased, becoming zero at the YIr_2 composition. The same results had been obtained in the earlier investigation and no doubt led to the suggestion that the superconductivity is due to the presence of a hypothetical phase of approximate YIr_4 composition. To investigate this possibility, we took new x-ray diffraction patterns of powdered samples of the same compositions using a Debye-Scherrer x-ray technique. The x-ray results indicated that no diffraction lines corresponding to a second phase were present in compositions up to 10 atomic per cent yttrium. The materials have a single-phase cubic structure with a relatively constant lattice parameter $a_0 = 3.8395$ Å, where a_0 is the distance between lattice sites. This structure, which is identical to and slightly larger than pure iridium ($a_0 = 3.8389$ Å), indicates that at most 1 atomic per cent yttrium is absorbed into the iridium lattice. The location of the remaining yttrium (up to 9 atomic per cent) remained a mystery.

We measured the low-temperature specific heats of the samples to determine how much of each sample was superconducting. Actual measurements for the $Y_{.10}Ir_{.90}$ system are shown in Fig. 8. The size of the specific heat discontinuity at T_c indicated the following percentages.

Composition	Superconducting Phase (%)
$Y_{.01}Ir_{.99}$	8
$Y_{.025}Ir_{.90}$	20
$Y_{.10}Ir_{.975}$	56
$Y_{.17}Ir_{.83}$	70

These results are similar to the results observed in the ac susceptibility

measurements and indicate that the superconductivity is indeed due to a bulk superconductor whose concentration increases as the yttrium content increases. The low-temperature specific heat measurements also gave very valuable information on the parameters $N(0)$ and θ_D. As shown in Fig. 9, the value of γ, which is proportional to $N(0)$, remains almost unchanged through most of the range, while the value of θ_D, which is inversely proportional to β, undergoes an enormous reduction.
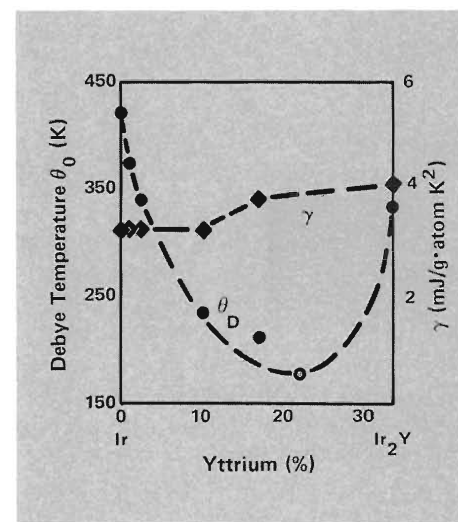

Fig. 9. *Measured values of the Debye temperature* θ_D *and the electronic specific heat parameter* γ *are shown for various compositions in the Y-Ir system. The electronic specific heat remains fairly constant, whereas the Debye temperature falls rapidly to a minimum and rises again as more yttrium is added to the iridium.*
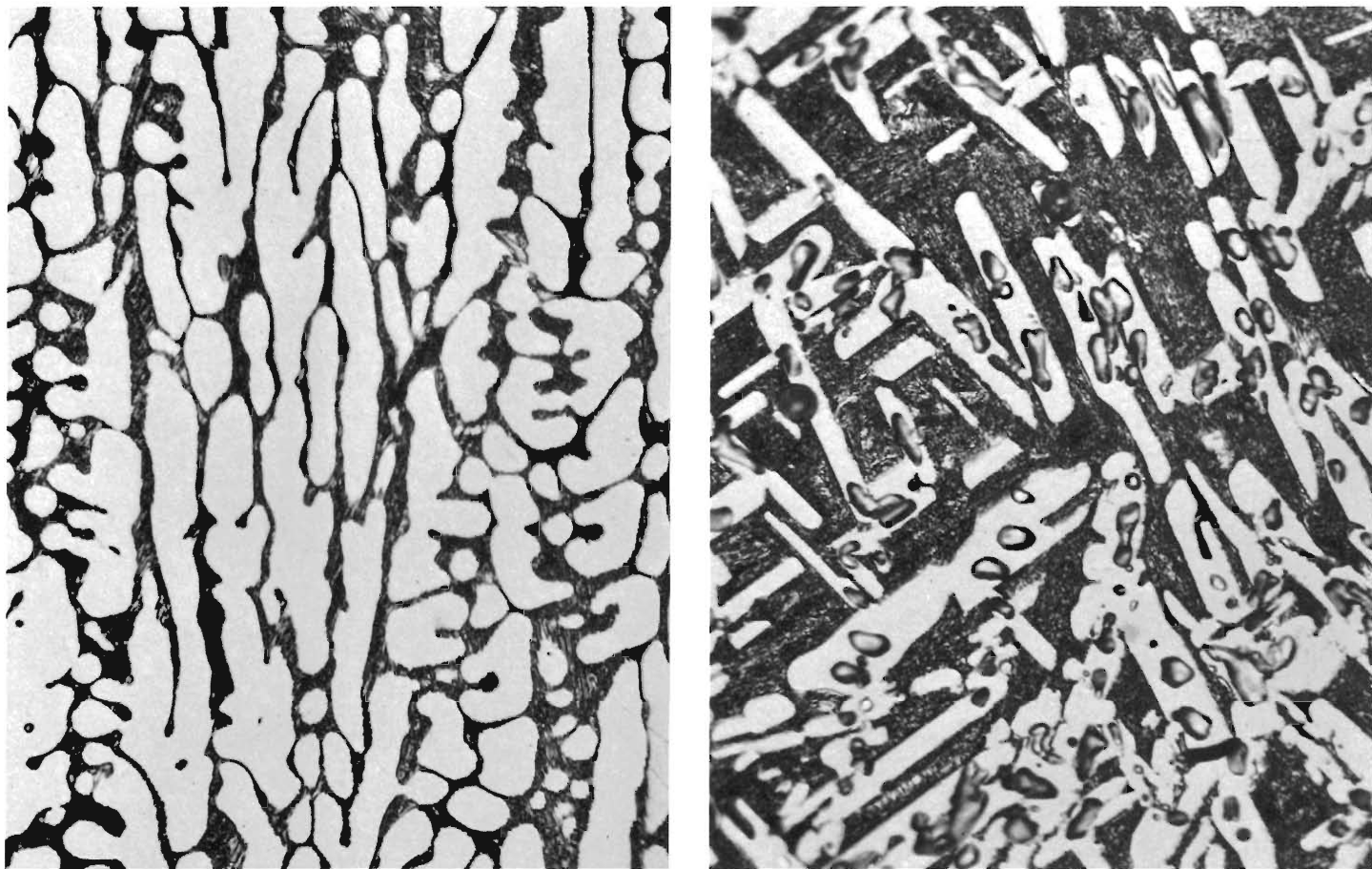
Fig. 10. Metallographic photographs of the various Y-Ir system compositions. The eutectic is visible in all four photographs as the darker regions. At left, this page ($Y_{.05}Ir_{.95}$), the light areas are pure iridium. As more yttrium is added to the system [at right ($Y_{.20}Ir_{.80}$)], the amount of eutectic increases; the light areas are probably pure iridium but the precise identification has not been made.

The x-ray diffraction studies indicated that in compositions up to 10 atomic per cent yttrium only one phase appeared to be present, a cubic lattice of iridium containing less than 1 atomic per cent yttrium. At this point, we believed that the iridium cubic phase was the superconductor, but two questions remained unanswered. Why do increases in the yttrium concentration cause increases in the amount of superconducting phase, and where is the excess yttrium located? The excess yttrium neither enters the iridium lattice nor forms enough of a second phase to account for more than a small fraction of the yttrium present. The mystery of the missing yttrium was solved when we examined the microstructure of the samples using conventional optical metallography and transmission electron microscopy. Microscopic examination showed that a fine-grained eutectic (Fig. 10) was present in all samples and that the amount of the eutectic increased in direct propor-

tion to the increase in the amount of bulk superconductor as determined by the low-temperature specific heat measurements. The x-ray results, the metallographic data, and the low-temperature specific heat measurements allow no other conclusion. The bulk enhanced superconductivity is associated with the eutectic and results from the extreme decrease in the lattice stiffness. The failure of the x-ray diffraction studies to detect the eutectic is surprising; it suggests that the structure must consist of extremely small crystallites.

Search for High-Temperature Superconductors

The search for methods to produce higher T_c materials has been the subject of innumerable investigations ever since superconductivity was first observed. It has taken such widely different approaches as the attempts of Little (1964)

to produce superconducting polymers, the studies of Abeles and coworkers (1966) on the effect of granular material on T_c, and the suggestion of Ginzburg (1968) on raising T_c by the formation of metal-dielectric sandwiches. Unfortunately, to date essentially no success has resulted from all these attempts.

With the development of the BCS theory, T_c was related to θ_D, $N(0)$, and V, the electron-phonon interaction parameter, as shown in Eq. (7). On this basis, a material with high θ_D, $N(0)$, and V values should have a high T_c. Unfortunately, V is not known for most materials and cannot be determined from other parameters. When V was ignored, it appeared that materials with high θ_D and $N(0)$ values would be high-temperature superconductors. Limited success was achieved in relating high $N(0)$ values to high T_c. The dependence of T_c on θ_D appears to be much more complex. We find many examples that support a correlation between high T_c
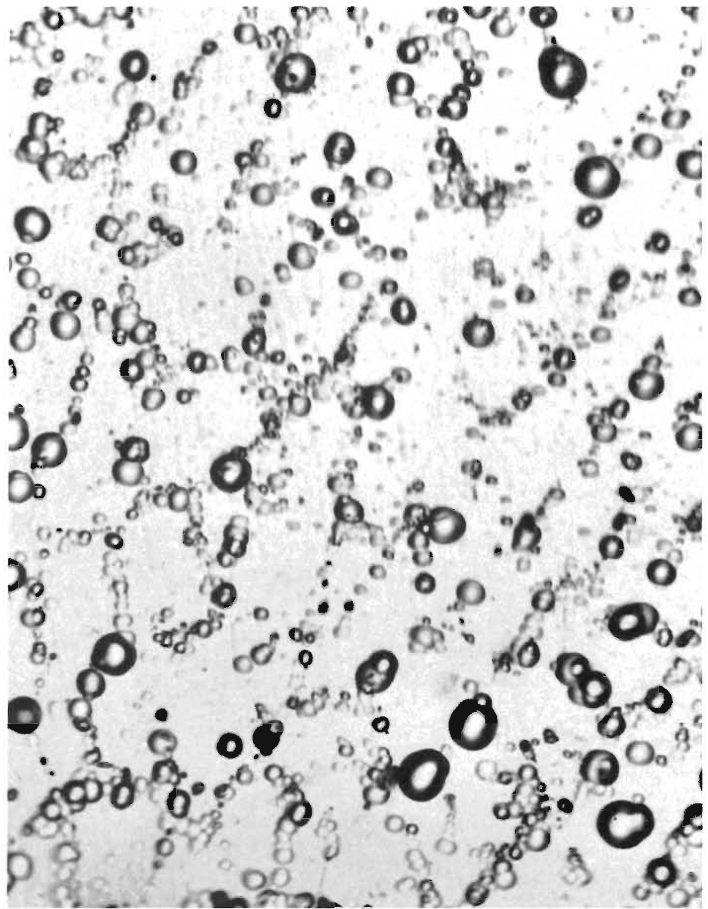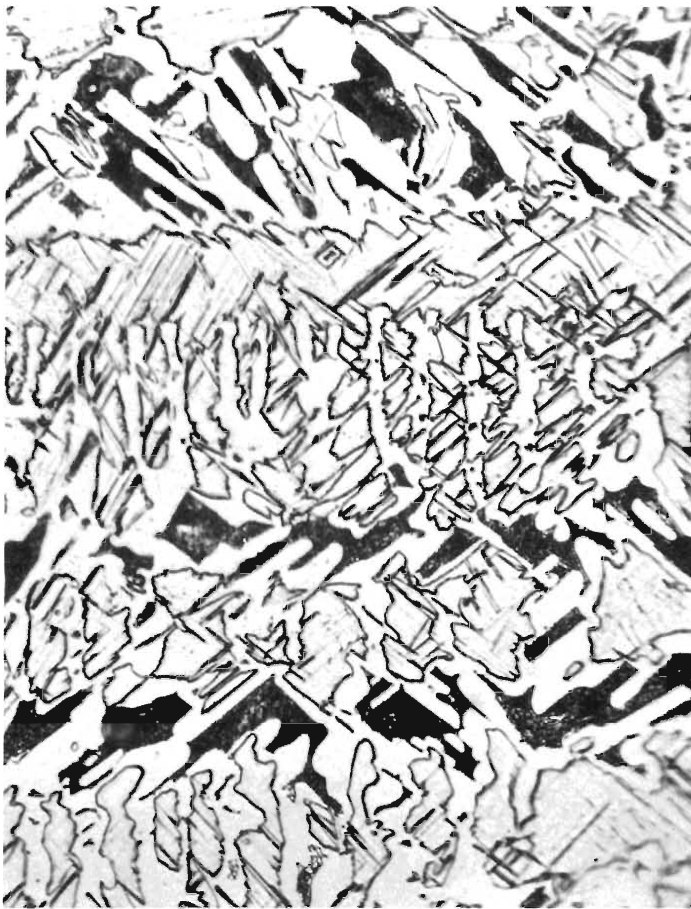
With further increase of yttrium [at left, this page ($Y_{.25}Ir_{.75}$)] the amount of eutectic begins to decrease; the light areas are probably YIr_2. At the right ($Y_{.30}Ir_{.70}$), the eutectic, the dark bubble-like structures, has almost disappeared. The lighter areas are YIr_2. The amount of eutectic for each composition is proportional to the percentage of material that is superconducting as measured by specific heat measurements. (1000X) Metallography by Ramiro A. Pereysa.

and high θ_D and many that contradict it. Technetium ($\theta_D = 454$ K) has a T_c of 8.9 K, whereas thallium ($\theta_D = 78$ K) has a T_c of 2.4 K. On the other hand, osmium ($\theta_D = 500$ K) has a T_c of only 0.66 K, whereas lead ($\theta_D = 108$ K) has a T_c of 7.2 K. The present belief is that the electron-phonon interaction parameter V and the Debye temperature θ_D are interrelated: V varies inversely with θ_D. The dependence of V on θ_D is not surprising since the electron-phonon interaction obviously varies with the lattice phonon frequency spectrum. Thus superconductivity should be favored in materials with high N(0) and/or low θ_D values.

Other investigators have observed T_c enhancement, but never to the extent found in the Y-Ir system. Some enhancement occurs in dilute alloys of titanium, zirconium, or hafnium with the transition metals of groups V to VIII. Of particular interest is the investigation of the Ti-Mo system by Collings and Ho

(1969). They found that the T_c of the α' phase increased gradually from 1.5 to 6 K as the molybdenum concentration was increased up to 4.5 atomic per cent. Low-temperature specific heat measurements indicated an increase in γ and a decrease in θ_D, whereas metallographic examination showed that a hexagonal-close-packed martensitic structure was forming. Because the increase in γ and, therefore, in N(0) was not sufficient to explain the increase in T_c, part of the enhancement was attributed to the lattice softening shown by the drop in θ_D. However, since both γ and θ_D were changing, the cause of the T_c enhancement was unclear.

In the Y-Ir system the situation is more straightforward. Because γ remained essentially unchanged while θ_D decreased, we can attribute the 30-fold increase in T_c directly to the modification of the lattice vibrations in the eutectic as compared to the vibrations in the iridium. This is the first documented case

of a system where the effects of θ_D and N(0) can be separated clearly and the enhanced T_c can be linked directly to the change in the lattice vibrations. Changing the lattice vibrations has been anticipated theoretically as a means to enhance superconductivity. However, the experimental search involved making tiny spheres. The belief was that the vibration patterns of only a few hundred atoms would be severely altered compared to the vibration patterns of the same atoms located in an essentially infinite matrix of the same material. The alteration should result in a dramatic change in the Debye temperature, similar to the change observed in the eutectic. Although it is mere speculation at this time, the possibility that the eutectic in the Y-Ir system is made up of tiny regions of well-ordered atoms that are only slightly affected by the neighboring regions should be considered. If that is so, then the eutectic may well be a bulk form of an ensemble of small particles.
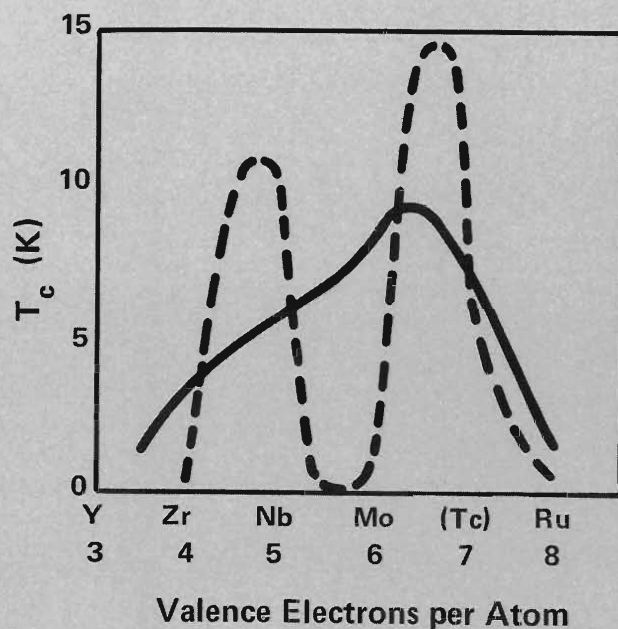
Fig. 11. The variation in T_c as a function of e/a for amorphous 4d transition metal alloys is shown by the solid line. The corresponding data for the same materials prepared in crystalline form are shown by the dashed curve. The distinct peaks for the crystalline materials have been broadened by preparing the materials in an amorphous state. The electronic levels appear to be blurred by the breakup of the crystalline structure.

Many implications now can be investigated. Within the field of superconductivity, the most obvious impact may be on amorphous materials. By definition, amorphous materials are disordered and noncrystalline; therefore their properties should be unaltered by radiation damage. Amorphous superconductors have been studied extensively as candidate materials for superconducting magnets in magnetic fusion reactors. Unfortunately, amorphous materials have low T_c. However, eutectics with high T_c and extremely small crystalline structures should exhibit similar resistance to radiation damage and should be useful in magnetic fusion applications.

Our work on eutectics suggests why amorphous materials have low T_c. Figure 2 shows the relationship between T_c and the e/a ratio for materials in crystalline form. When Matthias searched among the known superconductors for a relationship between T_c and the e/a ratio, he found two sharp peaks in the T_c curve at e/a ratios of 4.7 and 6.5 with sharp minimums between the peaks. These variations reflect the variation of N(0) in the elements and alloys across the periodic table. When Colver and Hammond (1973) prepared the same materials in the amorphous state, they found the peaks simply broadened. That is, the high T_c values were lowered and the low values were increased (Fig. 11). The simplest explanation of this result is that the sharp maxima in N(0) at certain compositions are blurred by the microscopic, liquid-like randomness of the atoms. To achieve high T_c in alloys, the N(0) blurring must be avoided. The eutectic may be the method of accomplishing this. The microscopic structure of many eutectics can be changed dramatically by varying their solidification conditions. Their particle size varies strongly with cooling

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rates and approaches the amorphous state with very rapid quenches. These changes in structure cause changes in many of the magnetic, mechanical, optical, and thermal properties. As has been demonstrated in the Y-Ir system, it should be possible to prepare eutectics with regions of crystallinity large enough to keep the $N(0)$ large and sharp, but small enough to ensure that the Debye temperatures are lowered dramatically. Such preparations could lead to much higher T_c materials and provide a tremendous impetus to the widespread application of superconductivity.

Understanding Eutectics

The results of the present study may prove to be even more important outside the field of superconductivity. In metallurgy, eutectics have been known and studied for a long time without real progress in understanding when they occur and why they have such altered properties. The lowering of a melting point by mixing one substance with another has been known for a long time—but not understood. No theory or even hypothesis will predict the occurrence of eutectics. Now, the enhancement of T_c for the first time opens the way to a basic understanding of eutectics. We now realize that lattice softening goes hand in hand with the melting point minimum in the eutectics. We now have an important new piece in the puzzle of eutectic behavior.

The world has relied on eutectics for a long time, from getting rid of ice with salt to making soft solder, and from welding, to alkaline liquid coolants in reactors. Finally, some understanding is on the way; with it comes the possibility of progress toward higher T_c, technologically more useful superconductors, and perhaps eventually a better understanding of many metallic alloys.
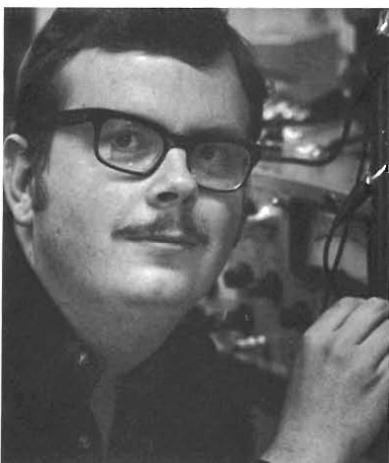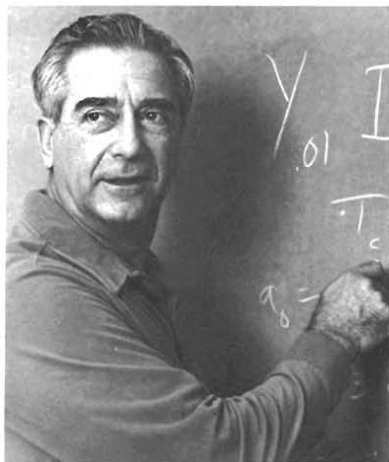
Angelo L. Giorgi earned his bachelor of science degree in chemistry in 1939, came to LASL in 1946, and received his Ph.D. in physical chemistry from the University of New Mexico in 1956. He has over 30 years of varied experience in research, development, and instrumentation in the fields of electrochemistry, radiochemistry, high-temperature phase studies, and cryogenics. His continuing investigations of superconducting and magnetic properties of various carbides and intermetallic compounds have resulted in discoveries of several new superconductors, a new itinerant electron ferromagnet, and the first itinerant antiferromagnet.

Gregory R. Stewart earned his bachelor of science degree cum laude from California Institute of Technology in 1971, and received his Ph.D. from Stanford University in 1975. He did postdoctoral work at Stanford and at the University of Kostanz, FRG. He joined LASL's CMB Division as a Staff Member in 1977, where he developed a new type of small-sample calorimeter and constructed a 7-T superconducting magnet. He is involved in characterizing new materials that range from high T_c superconductors of technological interest to lower T_c superconductors, where the interest is in understanding what makes superconductivity occur.

James L. Smith is best known for his definitive work on three of the five known superconducting actinides. He also has studied high-pressure phase transitions of americium. As an offshoot of the work described in the article, he has made interesting discoveries about dilute magnetism; for example, he has discovered magnets that are 100 times more dilute than any found before. He earned his bachelor of science degree at Wayne State University in 1965 and his Ph.D. in physics from Brown University in 1974. He has been a Staff Member in LASL's CMB Division since 1973.

Bernd T. Matthias is Associate Director of the Institute for Pure and Applied Physical Sciences and Professor of Physics at the University of California at San Diego, and part-time member of the technical staff of Bell Telephone Laboratories, Inc. He has been a consultant for LASL since 1957 and was named a Fellow of the Los Alamos Scientific Laboratory in 1971. He is a world authority on superconducting materials, having been involved in the discovery of more of these than any other individual. He is also well known for his discoveries of ferroelectrics and ferromagnets, and for his work on the questions of the coexistence of magnetism and superconductivity. He is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the Swiss Physical Society and a Fellow of both the American Physical Society and the American Association for the Advancement of Science. Matthias has received many scientific honors and awards, the two most recent awards being the Oliver E. Buckley Solid State Physics Prize in 1970, and American Physical Society International Prize for New Materials in 1979. The latter was for discovering unusually high temperature superconducting intermetallic compounds and alloys and demonstrating their usefulness in producing high magnetic fields for electric power technology and magnetic confinement of plasma. Originally from Frankfurt, Germany, he earned his Ph.D. from the Swiss Federal Institute of Technology in 1943.